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COMPACT REFRACTIVE IMAGING SPECTROMETER UTILIZING IMMERSED GRATINGS

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[0001] The United States Government has rights in this invention pursuant to Contract No. W-7405-ENG-48 between the United States Department of Energy and the University of California for the operation of Lawrence Livermore National Laboratory.

BACKGROUND

Field of Endeavor

[0002] The present invention relates to a spectrometer and more particularly to a compact reflective imaging spectrometer.

State of Technology

[0003] United States Patent No. 5,717,487 issued February 10, 1998 to Donald W. Davies, and assigned to TRW Inc., provides the following state of technology information, "A spectrometer is a known instrument for examining the spectral characteristics of light. Light emitted from or reflected by an object is received within the spectrometer and separated into its spectral components, such as the red, green and blue colored spectra as occurs in equal intensity when standard white light is so analyzed. The intensity of each such spectral component of that received light may be readily observed and measured. Each element of nature, molecular components, organic and inorganic compounds, living plants, man, animal and other substances is known to emit a unique spectrum that may be used as an indicium to identify the emitter. In past scientific work, the spectral analyses of a host of known elements, molecules, materials, living plants, gases and the like, has been compiled into a library. That library enables objects and

things to be identified solely by the spectrometric analysis of the light reflected therefrom. Thus, as example, by examining the spectral content of light reflected from the distant planets, astronomers identified the constituent elements, such as iron, forming those planets; by examining the spectral content of Gases emitted by factory smokestacks, scientists determine if pollutants are being emitted in violation of law or regulation; by examining the spectral content of land, the environmental engineer is able to determine the botanical fertility of a region and its mineral content, and, with subsequent observations, to determine the change in the environment with time; and by examining the spectral content of light reflected in multiple scans over a geographic region, military personnel identify camouflaged military equipment, separate from plant life, in that geographic region. The foregoing represent but a small number of the many known uses of this useful scientific tool."

[0004] United States Patent Application No. 2002/0135770 published September 26, 2002 by E. Neil Lewis and Kenneth S. Haber for an Hybrid Imaging Spectrometer, provides the following state of technology information, "Imaging spectrometers have been applied to a variety of disciplines, such as the detection of defects in industrial processes, satellite imaging, and laboratory research. These instruments detect radiation from a sample and process the resulting signal to obtain and present an image of the sample that includes spectral and chemical information about the sample."

[0005] United States Patent No. 6,078,048 issued June 20, 2000 to Charles G. Stevens and Norman L. Thomas for an immersion echelle spectrograph, assigned to The Regents of the University of California, provides the following state of technology information, "In recent years substantial effort has been directed to the problem of detection of airborne chemicals. The remote detection of airborne

chemicals issuing from exhaust stacks, vehicle exhaust, and various exhaust flumes or plumes, offers a non-intrusive means for detecting, monitoring, and attributing pollution source terms. To detect, identify, and quantify a chemical effluent, it is highly desirable to operate at the limiting spectral resolution set by atmospheric pressure broadening at approximately 0.1 cm.sup.-1. This provides for maximum sensitivity to simple molecules with the narrowest spectral features, allows for corrections for the presence of atmospheric constituents, maximizing species selectivity, and provides greater opportunity to detect unanticipated species. Fourier transform spectrometers, such as Michelson interferometers, have long been the instrument of choice for high resolution spectroscopy in the infrared spectral region. This derives from its advantage in light gathering power and spectral multiplexing over conventional dispersive spectrometers. For remote sensing applications and for those applications in hostile environments, the Fourier transform spectrometer, such as the Michelson interferometer, is ill suited for these applications due to the requirements for keeping a moving mirror aligned to better than a wavelength over the mirror surface. Furthermore, this spectrometer collects amplitude variations over time that are then transformed into frequency information for spectral generation. Consequently, this approach requires stable radiation sources and has difficulty dealing with rapidly changing reflectors or emissions as generally encountered in remote field observations, particularly from moving observation platforms. Furthermore, under conditions where the noise terms are dominated by the light source itself, the sensitivity of the instrument is limited by the so-called multiplex disadvantage."

[0006] United States Patent No. 5,880,834 issued March 9,1999 to Michael Peter Chrisp for a convex diffraction grating imaging spectrometer, assigned to

The United States of America as represented by the Administrator of the National Aeronautics and Space Administration, provides the following state of technology information, "There are three problems in designing an imaging spectrometer where light in a slice of an image field passing through an entrance slit is to be diffracted by a grating parallel to the slit and imaged onto a focal plane for display or recording with good spatial resolution parallel to the slit and good spectral resolution perpendicular to the slit: 1. Eliminating astigmatism over the spectrum on the image plane. 2. Removing field curvature from the spectrum focused onto the image plane. 3. Obtaining good spatial resolution of the entrance slit which involves eliminating astigmatism at different field angles from points on the entrance slit."

SUMMARY

[0007] Features and advantages of the present invention will become apparent from the following description. Applicants are providing this description, which includes drawings and examples of specific embodiments, to give a broad representation of the invention. Various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this description and by practice of the invention. The scope of the invention is not intended to be limited to the particular forms disclosed and the invention covers all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the claims.

[0008] The present invention provides a compact reflective imaging spectrometer. The compact imaging spectrometer comprises an entrance slit for directing light, a first means for receiving the light and focusing the light, an immersed diffraction grating that receives the light from the first means and defracts the light, a second means for receiving the light from the immersed

diffraction grating and focusing the light, and an image plane that receives the light from the second means. In one embodiment the immersed diffraction grating comprises a prism with three angles. In one embodiment the immersed diffraction grating comprises a prism with three angles that are around 51.7°, 36.2°, and 92.1°. In one embodiment the present invention provides a compact reflective imaging spectrometer apparatus, comprising an entrance slit for directing light, a first lens means for receiving the light and focusing the light, an immersed diffraction grating that receives the light from the first lens means and defracts the light, a second lens means for receiving the light from the immersed diffraction grating and focusing the light, and a detector that receives the light from the second lens means.

[0009] The invention is susceptible to modifications and alternative forms. Specific embodiments are shown by way of example. It is to be understood that the invention is not limited to the particular forms disclosed. The invention covers all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The accompanying drawings, which are incorporated into and constitute a part of the specification, illustrate specific embodiments of the invention and, together with the general description of the invention given above, and the detailed description of the specific embodiments, serve to explain the principles of the invention.

FIG. 1 is a raytrace illustrating an embodiment of a compact imaging spectrometer constructed in accordance with the present invention.

FIG. 2 shows the immersed diffraction grating in greater detail.

FIG. 3 is a raytrace illustrating another embodiment of a compact imaging spectrometer constructed in accordance with the present invention.

FIG. 4 is a perspective view of the raytrace illustrating the embodiment of a compact imaging spectrometer constructed in accordance with the present invention shown in FIG. 3.

DETAILED DESCRIPTION OF THE INVENTION

[0011] Referring now to the drawings, to the following detailed description, and to incorporated materials; detailed information about the invention is provided including the description of specific embodiments. The detailed description serves to explain the principles of the invention. The invention is susceptible to modifications and alternative forms. The invention is not limited to the particular forms disclosed. The invention covers all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the claims.

[0012] The present invention provides a compact imaging spectrometer based on lenses and an immersed diffraction grating. Small size for an imaging spectrometer is extremely important because it determines the requirements for the cryogenic cooling. If the spectrometer is small it can fly in a small UAV. Also, if the spectrometer is small it is person portable. Referring to FIG. 1 of the drawings, an embodiment of a compact imaging spectrometer constructed in accordance with the present invention is illustrated. This embodiment of the present invention is designated generally by the reference numeral 100.

[0013] FIG. 1 is a raytrace for the imaging spectrometer 100. The structural elements in the compact imaging spectrometer 100 include slit 101, collimating lens 102, immersed diffractive grating 103, objective triplet lens L1 104, objective

triplet lens L2 105, objective triplet lens L3 106, cold filter 107, and image plane 108.

[0014] The imaging spectrometer 100 has a size envelope that is smaller than spectrometers currently in use. The slit 101, collimating lens 102, immersed diffractive grating 103, objective triplet lens L1 104, objective triplet lens L2 105, objective triplet lens L3 106, cold filter 107, and image plane 108 fit within the envelope. The envelope is 8.2 cm by 7.9 cm by 1.4 cm or smaller. As shown in FIG. 1 the X axis is 8.2 cm and the Y axis is 7.9 cm.

[0015] Referring now to FIG. 2, the immersed diffractive grating 103 is shown in greater detail. The immersed diffractive grating material is Germanium. The immersed diffractive grating is on side B. The grating consists of equally spaced straight groves. The grating has 65 groves per mm. Angle AB is 51.7°, angle BC is 36.2°, and angle CA is 92.1°.

[0016] In operation of the compact imaging spectrometer 100, rays R1 diverge from slit 101. Collimating lens 102 collimates rays R1. Additionally collimating lens 102 images slit 101 to the immersed diffractive grating 103. Rays R2 are collimated. The immersed diffractive grating 103 angularly separates rays R2 according to wavelength. Rays R3 are collimated and angularly separated in wavelength. Longer wavelengths are angled to the left and shorter wavelengths to the right. Lenses 104, 105, and 106 in combination focus rays R3 with minimal distortions. Rays R6 converge and pass through cold filter 107. The cold filter 107 serves to filter out background light that is not of interest. Ray R7 focus onto the image plane 108.

[0017] The compact imaging spectrometer 100 is diffraction limited over the wavelength ranges with excellent spatial and spectral resolution. The spectral slit curvature has been corrected to less than one tenth of a pixel over the detector

arrays. This is the curvature of slit image on the detector at a single wavelength, which is a common problem with imaging spectrometer designs. The spatial mapping distortion has also been corrected to less than one tenth of a pixel over the full wavelength range. This means that the spectrum from a single point in the entrance slit will not wander from the center of a row of pixels by less than ± 2 microns for the compact imaging spectrometer 100 and ± 5 microns for the compact imaging spectrometer 200. Correcting the spectral slit curvature and the spatial mapping distortion with wavelength to less than one tenth of a pixel ensures that the images do not have to be resampled to correct for these effects.

[0018] The cold stop in the compact imaging spectrometer 100 is at the germanium grating. This ensures that the warm background radiation from outside the spectrometer entrance slit does not reach the detector array. This would cause an unacceptable degradation in the signal to noise ratio. The geometry of the compact imaging spectrometer 100 allows a transmissive cold stop to be used ahead of the grating, for even better thermal background reduction, but this also increases the grating size.

[0019] All the lenses in the compact imaging spectrometer 100 consist of spherical surfaces. The diffraction grating has the rulings immersed into a flat germanium surface. The grating can be diamond flycut with a blazed profile that will have maximum diffraction efficiency. In the compact imaging spectrometer 100, conventional gratings are used with equally spaced straight rulings. For the diffraction grating, light enters from the front germanium surface (which may have power) and then passes through the germanium to diffract off the grating rulings at the back surface. The diffracted light then propagates through the germanium and out. The grating is cut on the back of a wedged prism. The refractive faces of the prism may be spherical or plano. In the compact imaging

spectrometer 100 the power has been eliminated from the prism resulting in the grating being cut on a side of a wedged germanium prism. Although the grating is cut into germanium in this design, other materials such as zinc selenide are also suitable. For the compact imaging spectrometer 100, the prism is flat on all 3 faces and 3 lenses are used to focus the light into the detector array. Note that in this design the pupil is round.

[0020] The compact imaging spectrometer 100 solves the requirements for compact imaging spectrometers meeting the performance requirements given in Table 1. Small size is extremely important because it determines the requirements for the cryogenic cooling and also if the spectrometer can fly in a small UAV or if the spectrometer is person portable.

Table 1
(Imaging Spectrometer Performance)

Spectral Range	8 - 13.5 microns
F-number	5
Detector array	256 spatial x 256 spectral
Pixel size	40 microns
Entrance slit length	10.24 mm
Spatial distortion: change in spatial mapping with wavelength	<0.1 pixel (<±2 microns)
Spectral distortion: spectral smile	<0.1 pixel (<t2 microns)
Optical performance	Diffraction limited

[0021] The compact imaging spectrometer 100 is smaller than those currently in use and the cryogenic cooling requirements have been reduced thereby enabling its use in small unmanned aerial vehicles and for man portable instruments. The compact imaging spectrometer 100 can be utilized for remote sensing imaging spectrometers where size and weight are of primary importance. The compact imaging spectrometer 100 has very good spectral and

spatial registration providing accurate spectral data for spectral retrieval algorithms. This avoids having to resample the images to correct for these defects, which has the disadvantage of creating spectral mixing between pixels and reducing the sensitivity and accuracy of the retrieval algorithms.

[0022] The compact imaging spectrometer 100 uses smaller cryogenic coolers facilitating their using in portable (man carried) gas detection systems and in small unmanned aerial vehicles for remote gas detection. The compact imaging spectrometer 100 has application for homeland defense to check for the presence of biological or chemical weapons without entering the contaminated areas. The compact imaging spectrometer 100 also has application for the covert remote sensing of sites not accessible to United States forces. The compact imaging spectrometer 100 can be used for commercial remote sensing where portability is important. The compact imaging spectrometer 100 can be used for pollution detection, and remote sensing of agricultural crops, and geological identification. The compact imaging spectrometer 100 can also be used for the remote monitoring of industrial processes.

[0023] Referring to FIGS. 3 and 4 of the drawings, another embodiment of a compact imaging spectrometer constructed in accordance with the present invention is illustrated. This embodiment of the present invention is designated generally by the reference numeral 300. FIG. 3 is a raytrace for the imaging spectrometer 300. FIG. 4 provides a perspective view of the raytrace for the compact imaging spectrometer 300. The structural elements in the compact imaging spectrometer 300 include slit 301, collimating lens 302, mirror 304, immersed diffractive grating 303, lens 305, and detector array 306.

[0024] The imaging spectrometer 300 has a size envelope that is smaller than spectrometers currently in use. The included slit 301, collimating lens 302, mirror

304, immersed diffractive grating 303, lens 305, and detector array 306 fit within the envelope. The envelope is 3.4 cm by 1.4 cm by 1.2 cm or smaller. As shown in FIG. 3 the X axis is 3.4 cm and the Y axis is 1.4 cm.

[0025] The immersed diffractive grating material is Germanium. In operation, the compact imaging spectrometer 300 is diffraction limited over the wavelength ranges with excellent spatial and spectral resolutions. The spectral slit curvature has been corrected to less than one tenth of a pixel over the detector array. This is the curvature of the slit image on the detector at a single wavelengths, which is a common problem with imaging spectrometer designs. The spatial mapping distortion has also been corrected to less than one tenth of a pixel over the full wavelength range. This means that the spectrum from a single point in the entrance slit will not wander from the center of a row of pixels by less than ± 2 microns for the compact imaging spectrometer 300 and ± 5 microns for the compact imaging spectrometer 300. Correcting the spectral slit curvature and the spatial mapping distortion with wavelength to less than one tenth of a pixel ensures that the images do not have to be resampled to correct for these effects.

[0026] The cold stop in the compact imaging spectrometer 300 is at the germanium grating 303. This ensures that the warm background radiation from outside the spectrometer entrance slit does not reach the detector array. This would cause an unacceptable degradation in the signal to noise ratio. The geometry of the compact imaging spectrometer 300 allows a transmissive cold stop to be used ahead of the grating, for even better thermal background reduction, but this also increases the grating size.

[0027] All the lenses in the compact imaging spectrometer 300 consist of spherical surfaces. The diffraction grating 303 has the rulings immersed into a flat germanium surface. The grating can be diamond flycut with a blazed profile

that will have maximum diffraction efficiency. In the compact imaging spectrometer 300, gratings are used with equally spaced straight rulings. For the diffraction grating, light enters from the front germanium surface (which may have power) and then passes through the germanium to diffract off the grating rulings at the back surface. The diffracted light then propagates through the germanium and out. The grating is cut on the back of a wedged prism. The refractive faces of the prism may be spherical or plano. In the compact imaging spectrometer 300 the power has been eliminated from the prism resulting in the grating being cut on a side of a wedged germanium prism. Although the grating is cut into germanium in this design, other materials such as zinc selenide are also suitable.

[0028] Small size is extremely important because it determines the requirements for the cryogenic cooling and also if the spectrometer can fly in a small UAV or if the spectrometer is person portable. The compact imaging spectrometer 300 solves the requirements for compact imaging spectrometers meeting the performance requirements given in Table 1 above.

[0029] The compact imaging spectrometer 300 is smaller than those currently in use and the cryogenic cooling requirements have been reduced thereby enabling its use in small unmanned aerial vehicles and for man portable instruments. The compact imaging spectrometer 300 can be utilized for remote sensing imaging spectrometers where size and weight are of primary importance. The compact imaging spectrometer 300 has very good spectral and spatial registration providing accurate spectral data for spectral retrieval algorithms. This avoids having to resample the images to correct for these defects, which has the disadvantage of creating spectral mixing between pixels and reducing the sensitivity and accuracy of the retrieval algorithms.

[0030] The compact imaging spectrometer 300 uses smaller cryogenic coolers facilitating their using in portable (man carried) gas detection systems and in small unmanned aerial vehicles for remote gas detection. The compact imaging spectrometer 300 has application for homeland defense to check for the presence of biological or chemical weapons without entering the contaminated areas. The compact imaging spectrometer 300 also has application for the covert remote sensing of sites not accessible to United States forces. The compact imaging spectrometer 300 can be used for commercial remote sensing where portability is important. The compact imaging spectrometer 300 can be used for pollution detection, and remote sensing of agricultural crops, and geological identification. The compact imaging spectrometer 300 can also be used for the remote monitoring of industrial processes.

[0031] While the invention may be susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and have been described in detail herein. However, it should be understood that the invention is not intended to be limited to the particular forms disclosed. Rather, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the following appended claims.